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Electric propulsion system for electric vehicular technology: A review

Lalit Kumar*, Shailendra Jain

Department of Electrical Engineering, Maulana Azad National Institute of Technology (MANIT), Bhopal, MP, India

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ABSTRACT

In recent decades, factors such as the worldwide growing concern for pollution induced climate changes, increasingly stringent emission norms for vehicles and depleting petroleum resources coupled with volatility in their prices have motivated and accelerated development of sustainable and clean alternatives for transportation systems. Electrification of vehicular technology (EVT) is considered as a promising and sustainable alternative for future transportation systems. In evolution of EVT, instability of fuel price, fuel economy, range, performance and costs are the governing factors and prime concerns for researchers, auto manufacturers and customers. These factors are decided by the design of the electric propulsion system (EPS) for vehicular application and its suitable integration with various electrical and mechanical components. In this paper, a comparative overview of EVT along with a comprehensive analysis of EPS and a brief discussion on power flow control and management algorithms for EVT is presented. The paper also highlights the ongoing technological advancements and future challenges in the roadmap of EPS for the electrification of vehicular technology.

Contents

1. Introduction

In conventional vehicles, petroleum products (viz. petrol, diesel) are used to propel wheels through internal combustion engines (ICEs) as energy conversion units [1]. However, petroleum products are

* Corresponding author. Tel.: +91 9752 314 242; fax: +91 755 2670 562.
E-mail addresses: lalitsahu9@gmail.com, lalit_9900@yahoo.in (L. Kumar), sjain68@gmail.com (S. Jain).

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exhaustive and it is estimated that, at the present consumption rate, the current global petroleum resources will be used-up within the next 50 years [2]. Use of petroleum products primarily in transportation has also raised growing concerns about environmental pollution and subsequent climate changes. In the United States of America, for example, conventional transportation system accounts for 30–35% of total greenhouse gases (GHG) emission, causing significant global warming [3]. It is projected that world population will increase from the existing 6 billion to around 10 billion in the next 50 years while the number of vehicles in operation is set to increase from 700 million to 2.5 billion [4]. Given this scenario, meeting the worldwide energy demand for the present and future transportation systems with the least impact on the environment is an important developmental challenge.

In order to meet this challenge, novel concepts and innovations are being infused to make transportation systems more energy efficient, reliable and safe with zero or reduced emissions at an affordable cost. Majority of these innovations rely on electrification of conventional vehicular technology and are grouped under the genre of Electric Vehicular Technology (EVT). In EVT, ICE-based propulsion systems are being replaced by electric propulsion system, either partially or fully, to minimize fuel consumption and tailpipe emission. EVT involves specialization in mechanical, electrical, chemical and electronic aspects to achieve a reliable operation of electrified vehicles. Vehicles that employ EVT can be broadly classified as: electric vehicles (EVs), hybrid electric vehicles (HEVs), plug-in hybrid electric vehicles (PHEVs) and fuel cell vehicles (FCVs) [4–21].

In the last decade, successive development in vehicular electrification brought back the electrified vehicles in competition with ICE vehicle in terms of performance and globally emerged as sustainable alternative of conventional ICE based vehicles [13]. In addition automobile industries are shifting towards more fuel efficient, improved performance, higher degree of reliability, durability, safety and added comforts [23,24]. Thus, significant efforts

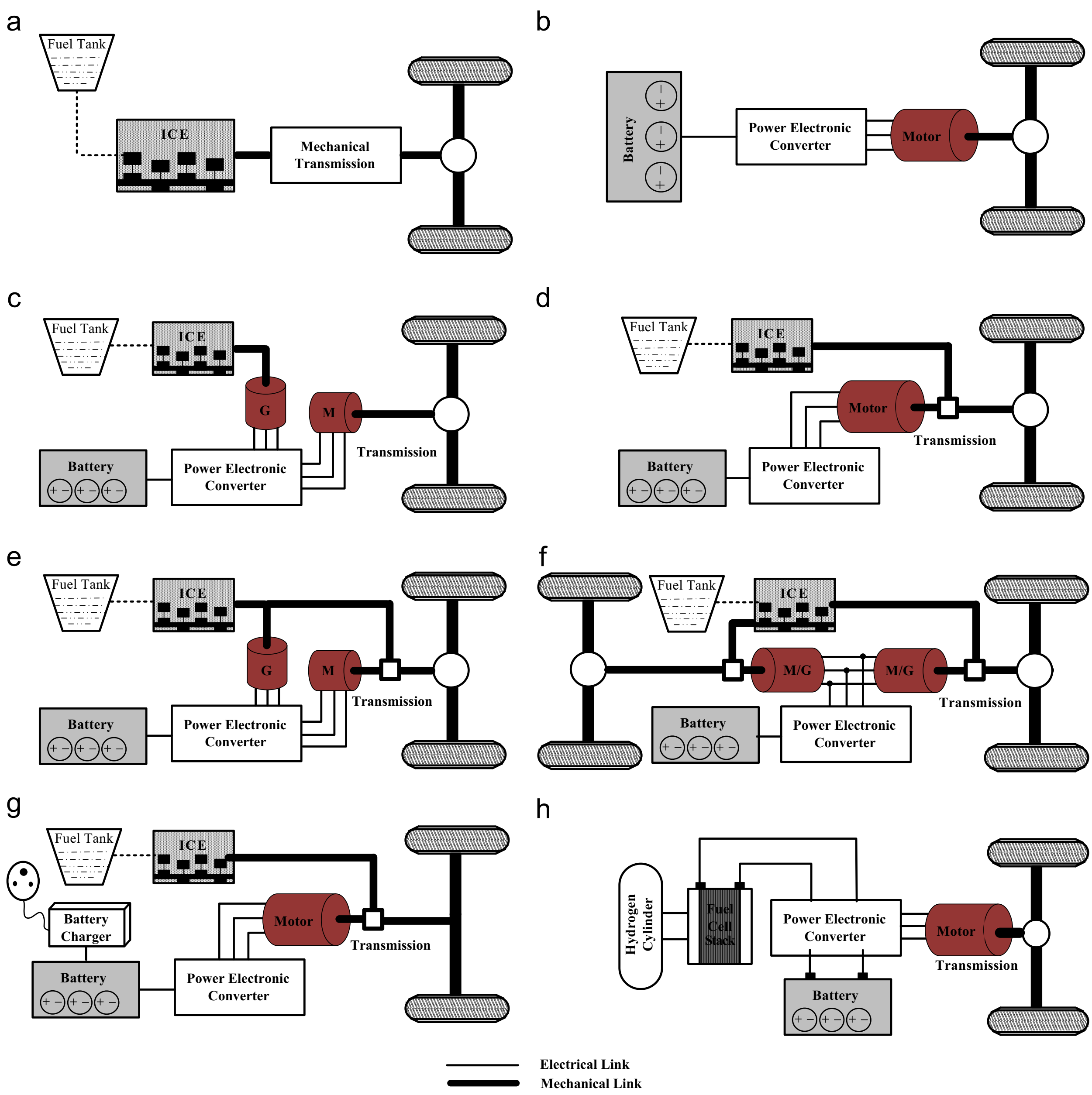

Fig. 1. Architecture and configuration of different vehicles (a) ICE vehicle; (b) battery electric vehicle; (c) series hybrid vehicle; (d) parallel hybrid vehicle; (e) series-parallel hybrid vehicle; (f) complex hybrid vehicle; (g) plug In hybrid vehicle; (h) fuel cell vehicle.

and resources are being spent by leading car manufacturers and government to meet market expectations at affordable cost. The sustainable growth and commercialization of multidisciplinary EVT mostly rely on substantial technological advancement of EPS and its components, especially energy source and storage system which act as bottleneck of the technology [4,29].

EVT, essentially, has three components: (1) vehicle architecture and configuration; (2) electric propulsion system including energy storage system (ESS); power electronic converter (PEC), electric motor (EM), and electronic controller (EC); and (3) power flow control and optimization algorithm. There are plenty of review papers and literature that deal individually with topological architecture and configuration [4–18], energy source and storage systems [31–59], electrical machines [60–79], power electronic converters [80–96], power flow management and control strategy [97–107]. However, a holistic, state-of-the-art review of EVT is largely missing. There is also a lack of literature on EPS and its different components and their suitable integration for vehicular application.

This paper presents the state-of-the-art understanding of EPS in conjunction with all other crucial constituents of a fully/partially electrified vehicular system. The paper is intended to offer a unified update of recent advancements in the development of EPS in the context of EVT. In addition, the paper also highlights current techno-economic issues and future challenges to mark potential research issues in this area of critical global importance.

The paper is organized as follows. Section 2 describes the classification of vehicles along with comparison amongst ICEs/EVs/HEVs/PHEVs/FCVs. Section 3 presents a detailed overview of EPS

Table 1
Different characteristic of ICEV/EV/HEV/PHEV/FCV [8].

Characteristics	Propulsion system	Energy storage	Energy source infrastructure	Advantages	Drawbacks	Important issues
ICE vehicles	• ICE based drives	• Fuel tank	• Petroleum products with refueling station	• Matured technology • Fully commercialized • Better performance • Simple operation • Reliable • Durable	• Less efficient • Poor fuel economy • Harmful emission • Comparatively bulky	• Fuel economy • Harmful emission • Highly dependency on petroleum products
EVs	• EPS based drive	• Battery • Ultra capacitor • Flywheel	• Electrical energy with charging facilities	• Energy efficient • Zero emission • Independency from petroleum products. • Quite • Smooth operation • Commercialized	• Limited driving range • Higher recharging time • Poor dynamic response	• Size and weight of battery pack • Vehicle performance • Infrastructure for charging station
Hybrid EVs	• EPS and ICE based drive	• Fuel tank • Battery • Ultra capacitor • Flywheel	• Electrical power • Petroleum products with refueling station	• Higher fuel economy • Very low emission • Long electric driving range • Reliable • Commercialized • Durability	• Costly • Bulky • Complex system • Complexity in control algorithm • Increased component count	• Power management of multi-input source • Size and weight of battery pack and ICE • Integration of components
Plug in HEVs	• EPS and ICE based drive	• Fuel tank • Battery • Ultracapacitor • Flywheel	• Electrical power with charging station • Petroleum products with refueling station	• Lower emission • Higher fuel efficient • Extended electric driving range • V2G or G2V capability • Partially commercialized • Quite and smooth operation	• Higher complexity • Impact on grid • Higher initial cost • Sophisticated electronic circuitry • Battery technology	• Size and weight of battery pack and ICE • Charging station infrastructure • Power flow control and management • Impact on grid
FCVs	• EPS based drive	• Fuel cell stack • Battery • Ultra capacitor	• Hydrogen cylinder or hydrogen enriched fuel • Hydrogen refiner and refueling station	• Ultra low emission • Highly efficient • Independency from petroleum products • Competent driving range • Reliable • Durable • Under development	• High cost • Slow transient response • Not commercialized yet • Sophisticated electronic controllers	• Cost of fuel cell • Cycle life and reliability • Infrastructure for Hydrogen conditioning, storage and refilling system

and their components including significance of EPS, status of their components, fundamentals of the energy storage system, electric motors, power electronic converters and electronic controllers and related key issues. Power flow management and respective control algorithms are discussed in Section 4 of the paper. Finally, Section 5 summarizes main conclusions of the review.

2. Classification of EVT

The vehicular technology can be classified as ICE-based and EPS-based which are driven by EPS either fully or partially. The significant drawbacks of the conventional ICEV are poor efficiency to convert the fuel into useful power and excessive tailpipe emission that has harmful impact on the environment [5,25]. To overcome these drawbacks of ICEV, EVs have been proposed. A battery operated EV offers numerous advantages over ICE-based vehicle such as zero emission, high efficiency, independence from petroleum products, safer, quieter and smoother operation [4–10]. Moreover, while the maximum efficiency of an ICEV ranges between, 30% to 35%, the EPS based vehicle can operate with a peak efficiency of around 90% [27].

The significant disadvantages of EVs include large battery charging time, lower flexibility and limited dynamic performance. An important limitation of battery operated EV is its limited operating range per cycle of battery charge. This limitation acts as a major bottleneck of the technology [4,5]. To improve these and other disadvantages, advanced electrified vehicles such as hybrid electric vehicles, plug-in HEVs and fuel cell vehicles have been proposed [4–21]. These advanced vehicles are not only capable of competing against the conventional ICE vehicles in terms of the performance but are also able to give higher fuel efficiency and low tailpipe emission [28].

Different types of electrified vehicles have their own capabilities and limitations in terms of emission rate, performance, fuel efficiency, durability, size, weight, cost, safety and comfort. Among different types of EVs, the Hybrid Electric Vehicle (HEV) is the only one that currently has the potential to compete with the ICE vehicle in terms of performance, and all driving profiles and offers advantages like extended electrical range of operation, good fuel economy, higher efficiency, sufficient onboard power and better dynamic response [5–10]. However, integration of automobile technology with electrical technology adds complexity in controls, and makes the HEV vehicle system comparatively bulky and costly. At present, HEV technology is rated as a promising technology which is growing rapidly and capturing significant market space at a fast growth rate [7,8]. Plug-in HEVs are currently at the commercialization stage. To be commercially viable, they require good energy policies and infrastructure for charging stations in the near future [13–17]. The efficiency analysis from well-to-wheels, the concept of vehicle-to-grid (V2G), grid-to-vehicle (G2V) and the impact of charging station on the grid are the major issue which are being researched for successful commercialization of plug-in HEV [7,16–19]. On the other hand, fuel cell vehicles, powered by hydrogen, are considered as the future of EVT [20–22]. The topological architecture and configuration of different types of IEC vehicle and EVTs are shown in Fig. 1 while the comparative analyses and corresponding issues of ICEV and different types of EV are summarized in Table 1.

Table 2
Current status and future target for EPS [30].

Characteristic	R&D status	Target	
	2010	2015	2020
Cost ($/kW)	< 19	< 12	< 8
Power density (kW/L)	> 1.06	> 1.2	> 1.4
Specific power (kW/kg)	> 2.6	> 13.5	4.0
Efficiency (%)	90	93	95

3. Electrical propulsion system

The function of the electric propulsion system (EPS) is like the heart of the EVT. EPS includes energy source and storage system (ESSS), electric motor (EM), power electronic converter (PEC) and electronic control unit (ECU) as major components. Suitable integration of these components is necessary for the EVT to compete against the conventional ICE based vehicle technology [26,27]. In order to achieve the vision of sustainable EVT, EPS must address important issues like driving profile, weight and volume of the vehicle, reliability and flexibility, compact packaging and installation, cooling system and maintenance, these all at an affordable costs [8–11]. At present, major challenge in EPS configuration is to design and implement electrical machines and power electronic converters which give better performance and which can be easily integrated for the next generation vehicles. The sizeable and suitable integration of different components of EPS needs substantial research and development from component level to system level. This integration faces many technical, nontechnical and societal challenges including high cost of motor material, low interest of power electronic component manufacturers and limited battery technology [29,30]. A synthesis of current research and development issues, future targets for the EPS technology is presented in Table 2. The development of viable EVT based on advanced EPS necessitates the targeted planning and collective efforts which will lead to increased performance, efficiency and reliability, while lowering cost, weight, and volume of

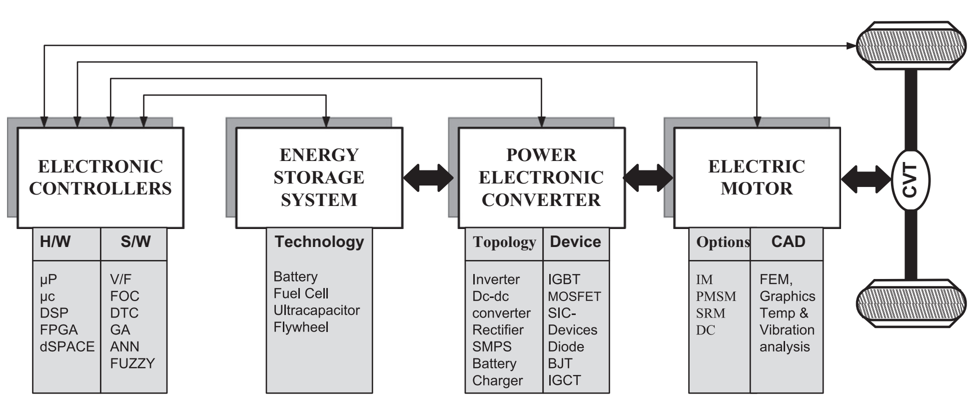

Fig. 2. Architectural overview of electric propulsion system [4].

the system. It will also narrow the gap between research and development of EPS and its industrial adoption with successful commercialization.

Fig. 2 shows a functional block diagram of EPS, including possible types of electronic controller, control hardware, software algorithms, energy storage systems, power converter devices/topologies, and electrical motors and their computer aided design methodologies. Nowadays CAD or FEM analyzed induction motors and PM motors are favored. In the power converter technology, PWM/IGBT inverters are the most popular along with bidirectional dc/dc boost converter. With regard to control technology, microprocessor or DSP-based vector control and direct torque control technology are very common [27].

3.1. Energy sources

The strength of the electric energy source and the storage system (ESSS) plays vital role in vehicular electrification. Basically, ESSS includes the source (fuel cell) and onboard energy storage device (battery, ultra-capacitor and flywheel) [31,32]. Battery and fuel cell produce onboard electrical energy by means of electrochemical energy conversion but the battery stores the energy whereas fuel cell generates the energy. Ultra capacitor, on the other hand, relies on electrostatic principle to store the energy and act as a source of high power density whereas flywheel stores energy in mechanical form. The efficiency, fuel economy and all-electric range (AER) of EVT are highly dependent on the onboard ESSS. The ESSS units must be sized such that they store sufficient energy (kWh) and provide adequate peak power (kW) for the vehicle to achieve the desired performance of all driving profiles [8,33].

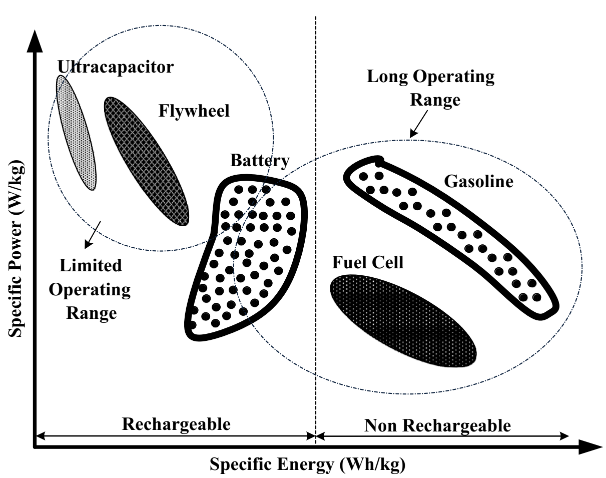

Fig. 3. Specific power vs specific energy characteristic for different energy sources [8].

The main factors that affect the design of ESSSs for vehicular application include energy density, power densities, life cycle, size, safety, maintenance, durability and recyclability at a projected cost [31–37]. The basic characteristics of specific power (W kg^{-1}) versus specific energy (W h kg^{-1}) of fuel cell, battery, ultracapacitor and flywheel is shown in Fig. 3 in comparison with petroleum fuel based ICE. It is obvious from Fig. 3, that each source of energy has specific characteristics and dominates accordingly. Suitable integration of these sources to form hybrid energy system (HES) is an interesting and challenging field for both researchers and manufacturers.

3.1.1. Battery

The battery converts chemical energy into electrical energy and vice-versa respectively at the time of charging and discharging. The electrochemical battery is a combination of independent cells which possess all the electrochemical properties. Each cell is capable to store or deliver a significant amount of energy individually or in combination based on their connections [40]. High energy density, modularity, flexibility and affordability are the factors that guide the battery technology on the roadmap of vehicle electrification [31]. In EVT, battery stores major onboard energy and contains high energy and power density to meet complete driving cycles of vehicle operation.

The basic characteristics of battery for different vehicles are different. High energy density batteries are required for EVs whereas a high power density battery is required for HEVs and FCVs. For PHEVs, intermediate battery technology is required so that it can match the energy density of an EV-battery and the power density of an HEV-battery [34]. However, batteries that fulfill the demand of PHEVs are yet to be designed specifically. A suitable battery type for EVT is the lithium based battery such as lithium ion and lithium polymer, lead acid and nickel based battery such as Ni–Cd and Ni–MH [34]. Among these, lead acid batteries are used for short term use because of their low energy density. On the other hand, lithium and nickel based batteries are preferred for medium and long term use. However, Ni–Cd and Ni–MH battery technologies are matured and their potential is fully explored. Therefore, significant improvement and cost reduction in these batteries in the coming years are least expected. The inherent advantages like high energy density, low weight and low cost of lithium based batteries invite attraction from automakers [31–38]. In Addition, the potential of lithium based batteries is still not fully explored and maturity level is yet to be achieved. Therefore Lithium based batteries are considered as futures battery technology to power the electrified vehicles. The dominating characteristics and comparison of different battery technologies are given in Tables 3 and 4 respectively.

Table 3
Characteristic of different battery technology [4].

Battery/parameters	Lithium based		Nickel based		Lead acid
	Ion	**Polymer**	**Ni–MH**	**Ni–Cd**	
Nominal cell voltage	3.6	3.0	1.2	1.2	2.0
Specific energy (Wh/kg)	35	100–200	60	40–60	35
Energy density (Wh/l)	70	150–350	220	60–100	70
Specific power (W/kg)	~200	>200	130	140–220	~200
Power density (W/l)	~400	>350	475	220–350	~400
Self-discharge (%/mon)	4–8	~1	30	10–20	4–8
Cycle life	500–1000	200–1000	300–500	300–700	250–500
Operating temperature (°C)	−20 to 60	0 to 60	−20 to 60	−40 to 60	−20 to 60

Table 4
Comparison of different battery technologies.
Source: C. Pilot " worldwide rechargeable battery 2003–2007/report/pdf". [4]

Advantages ON / OVER		Lithium Based		Nickel Based		Lead Acid
		Ion	**Polymer**	**Nickel Metal Hydride Ni-MH**	**Nickel Metal Cadmium Ni-CD**	
Lithium based	**Ion**	.	▪ Gravimetric ▪ Energy density ▪ Design characteristics ▪ Safety ▪ Price	▪ Price ▪ Safety ▪ Discharge rate ▪ Recyclability	▪ Operating temperature range ▪ Higher cyclability ▪ Price ▪ Safety ▪ Recyclability	▪ Higher cyclability ▪ Price ▪ Safety ▪ Recyclability
	Polymer	▪ Operating ▪ temperature range ▪ Higher cyclability	.	▪ Volumetric energy density ▪ Higher cyclability ▪ Price	▪ Operating temperature range ▪ Higher cyclability ▪ Price	▪ Higher cyclability ▪ Price
Nickel based	**Nickel Metal Hydride NiMH**	▪ Gravimetric energy density ▪ Volumetric energy density ▪ Operating ▪ temperature range ▪ Higher cyclability ▪ Voltage output ▪ Self discharge rate	▪ Gravimetric energy density ▪ Volumetric energy density ▪ Operating temperature range ▪ Self discharge rate ▪ Design characteristics	.	▪ Operating temperature range ▪ Higher cyclability ▪ Self discharge rate ▪ Price	▪ Higher cyclability ▪ Voltage output ▪ Price
	Nickel Cadmium NiCd	▪ Gravimetric energy density ▪ Volumetric energy density ▪ Voltage output ▪ Self discharge rate	▪ Gravimetric energy density ▪ Volumetric energy density ▪ Self discharge rate ▪ Design characteristics	▪ Gravimetric energy density ▪ Volumetric energy density		▪ Higher cyclability ▪ Voltage output ▪ Price
Lead Acid		▪ Gravimetric energy density ▪ Volumetric energy density ▪ Voltage output ▪ Self discharge rate	▪ Gravimetric energy density ▪ Volumetric energy density ▪ Self discharge rate ▪ Design characteristics	▪ Gravimetric energy density ▪ Volumetric energy density ▪ Self discharge rate	▪ Gravimetric energy density ▪ Volumetric energy density ▪ Operating temperature range ▪ Self discharge rate ▪ Reliability	
Absolute Advantages		▪ Gravimetric energy density ▪ Volumetric energy density ▪ Self discharge rate ▪ Voltage output	▪ Gravimetric energy density ▪ Volumetric energy density ▪ Self discharge rate ▪ Voltage output ▪ Design characteristics	▪ Volumetric energy density	▪ Operating temperature range ▪ Price	▪ Higher cyclability ▪ Price

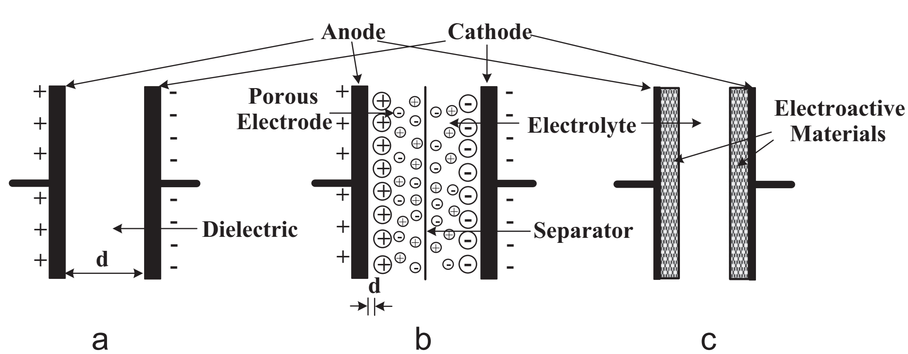

Fig. 4. Construction and operation of (a) capacitor; (b) ultracapacitor and (c) battery.
Source: http://blog.cafefoundation.org/?p=2561:Date 18/01/2013.

3.1.2. Ultracapacitor

Ultracapacitor is an electrochemical device which works on the electrostatic principle to store energy; therefore, it can be charged/discharged hundreds of thousands of time without degrading the performance [34,41]. Basically in ultracapacitor, porous carbon electrodes, which offer high surface area ($1000\ m^2\ g\ m^{-1}$) are impregnated with electrolyte and a small charge separation (10 Å) created by the dielectric separator between the electrodes as shown in Fig. 4(b). Appropriate modification in material selection and fabrication brought the ultracapacitor far away from conventional capacitor with very high capacitive (1000–5000 F) density [42]. Ultracapacitor stores energy higher than traditional capacitor but lower than battery and hence it can be used for applications, reserved for battery and capacitor. It offers high power density, long cycle life, and efficient operation. Since the rate of charge and discharge are determined by its physical properties, an ultracapacitor can release energy much faster (with more power) than a battery that relies on slow chemical reactions [41–44] Table 5.

Ultracapacitors have been used for ICE based vehicles, tanks and submarines starting due to its ability of burst power delivery. In EVT, ultracapacitors can be used as primary energy devices for power delivery during starting, acceleration and hill climbing, as well as for recovery of braking energy during regenerative braking. The combination of ultracapacitor with a battery improves the power performance of the former with greater energy storage capability of the latter [34]. It can downsize as well as extend the life of a battery, reduces maintenance and replacement costs. In the future, it is expected that ultracapacitor will become a major dominating technology in vehicle electrification however; desired energy density at reasonable weight and cost is a major concern. The application of ultracapacitor in vehicle electrification is under development and significant improvement has to be done for achieving maturity and commercialization in mass scale.

3.1.3. Flywheel

A flywheel that stores and delivers mechanical energy in the form of rotational kinetic energy has been researched for many decades but due to heavy weight and high cost, its implementation in vehicular system has been limited. Recent advancement in frictionless magnetic bearing, carbon-fiber composite materials, manufacturing technique and sophisticated power electronic controllers has accelerated the development of flywheel energy storage system (FESS) [45]. The numerous features of advanced FESS such as higher power density, reliability, efficiency, higher speed at reduced size and weight made it a potential candidate for energy storage system in EVT. The flywheel rim rotates in an evacuated containment that reduces frictional losses and ensures safety in case of failure [45–48].

A flywheel stores energy linear to its mass but square proportional to velocity from supply and delivers it to the load as per the requirement. The stored mechanical energy can be converted to electrical energy or vice-versa by means of integral motor/generator set and power electronic converters, as shown in Fig. 5. Flywheel gets charged by speeding up, as it accumulates mechanical energy and discharges by slowing down as it supplies mechanical energy to the EPS. The energy of regenerative braking can be recovered by charging the flywheel, which is further used for battery charging. Modern flywheels can store more energy and

Table 5
Comparison of ultracapacitor with conventional capacitor and battery.

Characteristics	Battery	Ultracapacitor	Conventional capacitor
Charging time	1–5 (h)	0.3–30 (s)	10^{-3}–10^{-6} (s)
Discharging time	0.3–3 (h)	0.3–30 (s)	10^{-3}–10^{-6} (s)
Energy densities(wh/kg)	10–100	1–10	< 0.1
Power densities(w/kg)	< 1000	< 10,000	< 100,000
Cycle life	1000–2000	> 500,000	> 500,000
Efficiency (%)	70–85	85–97	> 95

Table 6
Comparison of Flywheel and battery technology.

Characteristic	Flywheel	Lead acid battery
Technology	Promising	Proven
Storage mechanism	Mechanical	Chemical
Relative size	Small	Larger
Charge holding time	Hours	Years
Life span	More than 20 years	3–5 years
Power and energy density	High and low	Low and high

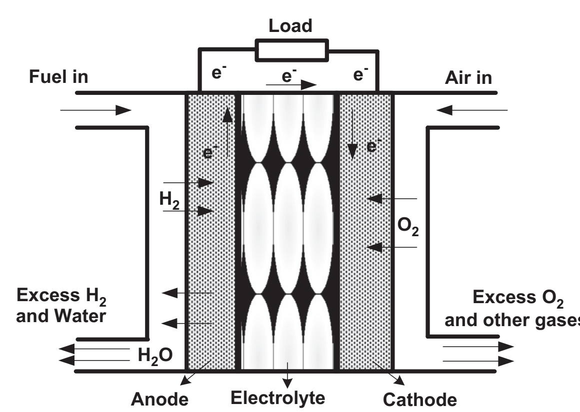

Fig. 6. Functional diagram of fuel cell construction and operation [55].

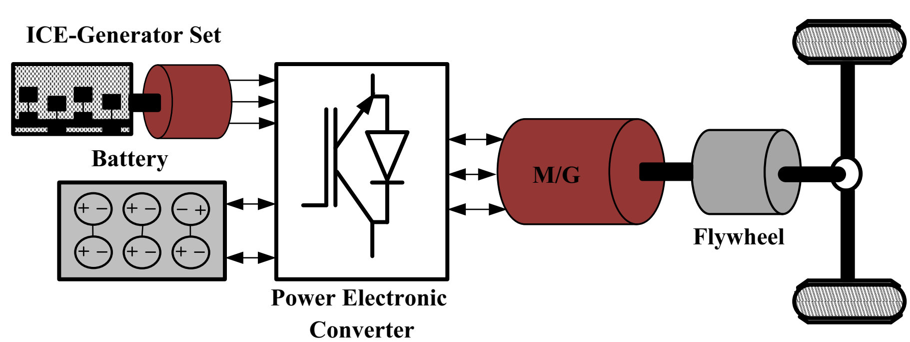

Fig. 5. Flywheel placement as energy buffer in EPS design.

Table 7
Comparison of fuel cell technology [56,57].

Characteristic	PEMFC	AFC	PAFC	MCFC	SOFC
Electrolyte	Perfluoro sulfonic acid	Phosphoric acid	Phosphoric acid	Molten carbonate	Solid oxide
Design and structure	Simple	Simple	Simpler	Complex	Complex
Temperature range	50–100 °C	80–100 °C	150–200 °C	600–700 °C	700–1000 °C
Starting up time	Lower	Low	Low	High	Higher
Stack size (kW)	<1–100	10–100	100–400	300kW-3 MW 300–300 MW	1–2 MW
Sensitivity	More	Less	Less	Lesser	Lesser
Efficiency (%)	40–60	50–60	40–50	45–60	50–65
Cell-life	2–10 μV/h	0–6 μV/h	2–4 μV/h	5 μV/h	0–8 μV/h
Advantages	• Low operating temperature • Quick start • Maintenance free	• Fast chemical reaction • Low cost • Less maintenance	• Less sensitive to impurity • Low cost • Simple structure	• High efficiency • Fuel flexibility • Variety of catalyst	• High efficiency • Solid electrolyte • Suitable for CHP • Fuel flexibility
Disadvantages	• Expensive catalyst • Fuel sensitive	• Fuel sensitive • Electrolyte management	• Expensive catalyst • Long start up time • Low current density	• High temperature • Long Start Up time • Low current density	• High temperature • Long Start Up time • Complex structure
Application	• Portable power • Vehicular application • DG	• Military • Space	• DG • Military	• Electric utility • DG	• Auxiliary power • Electric utility • DG

power than existing metal hydride or lead-acid batteries of similar weight and volume [45,46]. Unlike the battery and the ultracapacitor, flywheels are independent of in-depth discharge which improves its life cycle. The combination of the flywheel with battery improves overall power and energy rating of the ESS [47,48]. A comparison between flywheel and battery technology is shown in Table 6. It spins at a very high speed therefore safety, tensile strength of the material and location of placement of flywheel in EVT are prime concerns and needs to be dealt with properly.

Table 8
Comparison of different energy storage systems.

Characteristics	Battery	Ultracapacitor	Fuel cell	Flywheel
Mechanism	Chemical	Electrostatic	Chemical	Mechanical
Technology	Proven	Promising	Promising	Proven
Energy density	High	Low	Very high	Low
Power density	Low	Very high	Moderate	High
Charging time	Hours	Seconds	–	Minutes
Discharging time	Hours	Seconds	–	Minutes
Life	3–5 years	>10 years	10k–20k h	>20 years
Efficiency (%)	75–85	85–95	40–60	80–90
Environmental issues	Disposal	Less	Very less	Very less

3.1.4. Fuel cell

Recent technical advancements in fuel cell technology have constructed the roadmap for its application in EVT as on-board energy source. Significant advantages of a fuel cell are eco-friendly, simplicity, continuous power supply, durability and silent operation along with strict conformation to emission norms of vehicular systems [49,50]. In fact, a fuel cell combines the best features of IC engines (they can operate as long as fuel is supplied) and batteries (they can produce electricity directly from fuel, without combustion) thereby reducing emissions and noise and increases the efficiency. A fuel cell is an electrochemical device that uses hydrogen (H_2) as fuel and oxygen (O_2) from the air to produce electricity with water and heat as by-products as shown in Fig. 6. To speed up the rate of these reactions, a catalyst such as platinum is used.

In fuel cell, chemical energy of hydrogen is directly converted into electrical power, thus eliminating the intermediate steps of converting fossil fuel to heat and then electrical power which enhances efficiency comparatively. The specific energy of fuel cell is as good as gasoline; however, its specific power is much less; therefore the starting performances of fuel cell vehicles are very poor. Consequently, to improve the power density as well as starting performance, battery or ultracapacitor can be used in conjunction with the fuel cell for vehicular application [51–54]. Therefore it can be said that fuel cell and ultracapacitors are made for each other to lead a perfect ESS for automotives.

There are different types of fuel cells such as alkaline fuel cell (AFC), proton exchange membrane fuel cell (PEMFC), direct methanol fuel cell (DMFC), phosphoric acid fuel cell (PAFC), molten carbonate fuel cell (MCFC) and solid oxide fuel cell (SOFC) [49,55–57]. Among them, PEM fuel cell is prominent and is being used as an energy source in fuel cell vehicles. It offers easy start at low temperature, comparatively high power density, simple structure, small size, maintenance-free operation and ability to operate in hostile environment [57]. Table 7 shows a comparison of available fuel cell based on desirable characteristic for propulsion application. The dedicated efforts are given on infrastructure for hydrogen production, storage and refilling station which are major issues in fuel cell technology. In addition an intense research on exploration and possibility of other fuel cell in EVT has been going on. With technical advancement and suitable interfacing circuitry, significant cost reduction is expected in fuel cell based vehicles.

3.1.5. Hybrid energy system

It can be concluded that not only the power and energy densities but also voltage and current characteristics of different energy systems are different. Therefore, exclusive employment of one of the aforementioned energy sources cannot meet the energy and power demands of vehicle operation for all driving profiles [8]. Compared to ultracapacitors and flywheel, a battery and a fuel cell have much higher specific energy but much lesser specific power as depicted in Table 8. Employment of these energy systems alone results in higher cost, weight and volume [34,51]. However, when these different energy systems are combined, an energy system with high power and high energy density can be obtained. Such kind of an energy system is termed as a hybrid energy system

(HES), where batteries and/or fuel cell supply the energy demand and the ultracapacitors and/or flywheel supply the power demand [58,59]. The combination of energy system can be chosen on the basis of vehicles design, operating profiles and application. A schematic of hybrid energy system is shown in Fig. 7 that integrates all energy systems discussed above. The prime concerns of hybrid energy system formation are its suitable integration, life expectancy, maintenance, cost, durability and reliability.

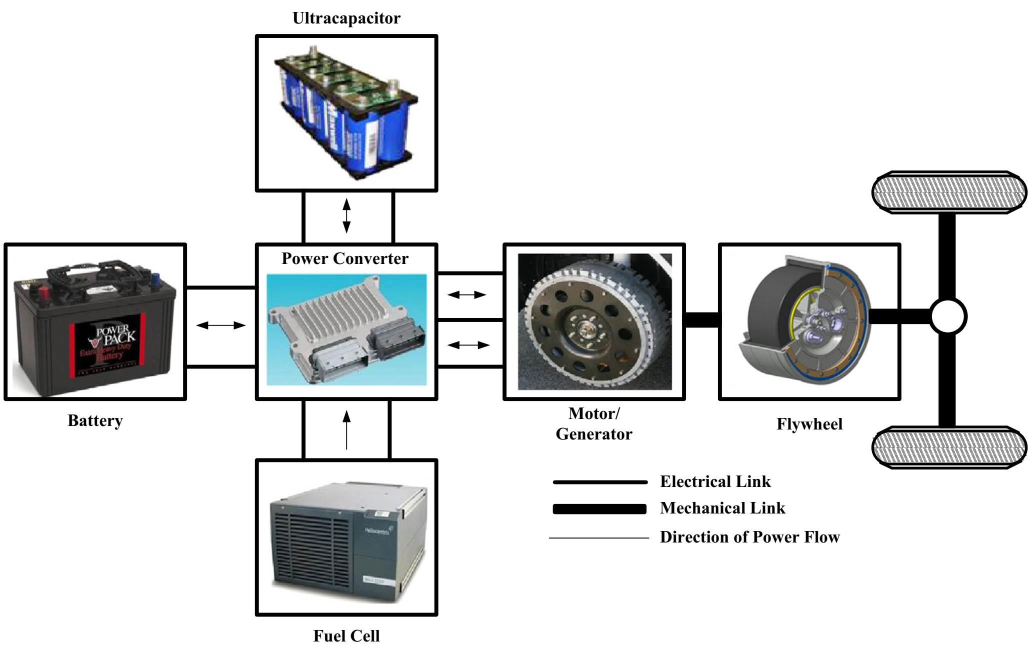

Fig. 7. Hybridization of energy source for EVT.

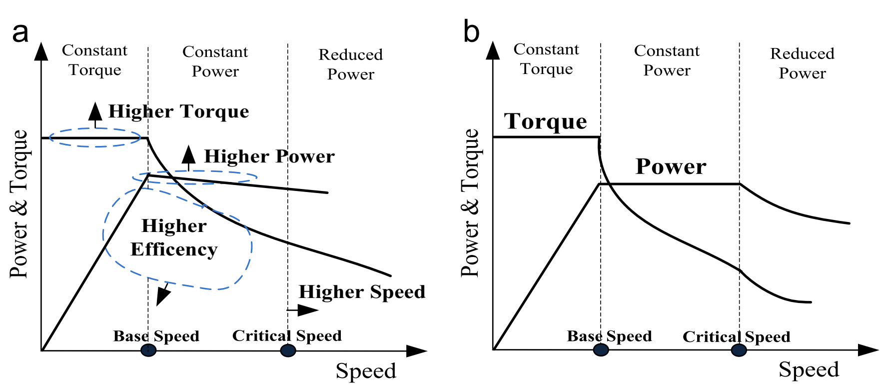

Fig. 8. (a) Desired torque–speed characteristic of vehicle propulsion system, (b) Standard torque–speed characteristics of electric motors [62].

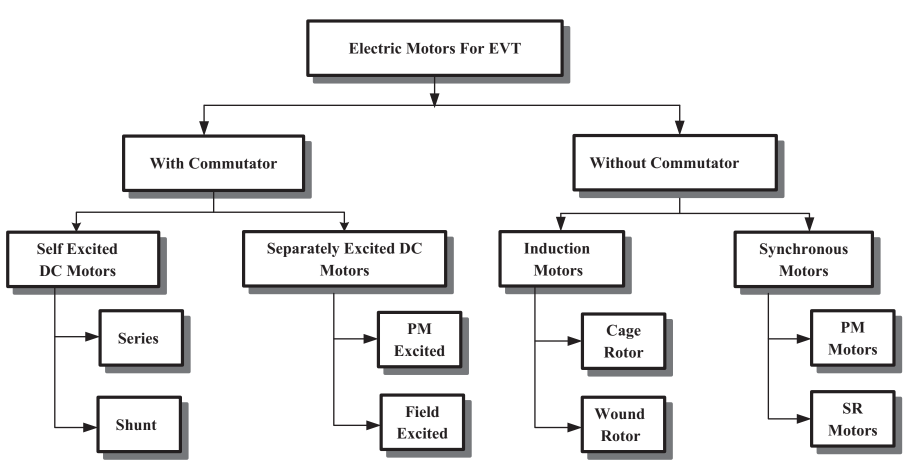

Fig. 9. Classification of electric motor for EPS.

3.2. Electric motor

In EVT, the electric motor needs to go through frequent starts and stops, high rate of acceleration and deceleration, such as low speed hill climbing and high speed cruising along with different environmental and hostile conditions. Industrial motors, on the other hand, are usually operated at rated speed under common circumstances [27]. Thus, the electric motors used in EVT cannot be compared with motors being used for industrial processes. The electric motors used for EPS should be able to satisfy some basic characteristic for efficient operation. These characteristics are: high torque for starting and low speed hill climbing operation; high power density for acceleration and high speed cruising for highway; high efficiency over wide torque and speed range; suitability for regenerative braking; over load capability during certain period of time; controllability, high reliability and robustness at affordable costs. In addition, fault tolerant capability, minimum torque ripple, temperature management and low acoustic noise are other important issues for design consideration [60–65]. Suitability of electric motor in propulsion application should be strongly approved by torque-speed characteristic illustrated in Fig. 8(a). Moreover, the standard torque-speed characteristic of EPS is shown in Fig. 8(b).

The choice of electric motor is the key factor in overall EPS design. A brief classification of family of electric motor for EPS is summarized in Fig. 9. The commonly used electric motors for EPS include DC motor, induction motor, permanent magnet (PM) motor and switched reluctance (SR) motor. Existing literature indicate that squirrel cage rotor induction motors and PM motors are best suitable options. Also, SR motors are gaining more popularity and becoming reliable alternative for the future while use of DC motors is declining gradually. The cross sectional view of different electric motor is shown in Fig. 10.

The recent trends indicate that the R&D in motors is focused on motor concepts that do not require rare earth (RE) magnets and exploration of less expensive materials for laminations and cores are being researched [30,68]. Development and refinement of less expensive magnets like ALNICO and Ferrite for PM motor are being researched. In addition to that issues like design and development of PM motors based on smaller magnets or less-expensive magnets like ALNICO and Ferrite. In addition, development in advanced scalable packaging designs and materials to reduce losses, improve heat removal, and increase efficiency [29]. Table 9 shows the contributing parts of the motor with respect to cost and weight.

3.2.1. DC motor

Traditionally, a DC motor has been used prominently for EPS due to its high starting torque and simple speed control. The torque-speed characteristic of DC motors exhibit good compliance for propulsion application; however, the inherent disadvantage of bulky construction, low efficiency and the presence of mechanical commutators and brushes that aggravate maintenance requirements, limit its use in light, high speed and maintenance-free vehicle application in hostile conditions [60–63]. Nevertheless, due to their simple speed control and technical maturity, DC motors are prominent for low power EPS. Technological advancements in power electronics converters and switches have helped to replace DC machines with commutatorless motors such as induction motors, PM motors and SR motors. The commutatorless motors offer some tremendous advantages such as high power density, higher efficiency, more reliable and maintenance free operation with wide speed range over the conventional DC motors [63].

3.2.2. Induction motor

Induction motor (IM) based propulsion systems are mature and are being extensively accepted as a dominating candidate for EPS among various commutatorless motors. The numerous attractive features of IM are its simplicity, high reliability, robustness, wide speed range, low maintenance, low torque ripple/noise, low cost, established power electronic converters and ability to operate in hostile environment [60–65]. The behavior and performance characteristics of DC series motors can also be achieved with induction motor by employing well matured field oriented control (FOC) that provides decoupling of torque control from field control [69]. The dynamic performance of IM can be further improved either by applying vector control or direct torque control (DTC) technique [71,72]. High speed operation with extended constant power range of up to 4–5 times the base speed can be achieved by flux weakening which is one of the desirable requirement for vehicle operation [62,69]. Although, the high speed operation and constant power range is limited by its pullout torque.

With proper choice of inverter; supply voltage and frequency can be varied to achieve high starting torque as much as maximum torque while keeping starting current low. Apart from the various advantages there are several disadvantages such as high losses, poor power factor, low efficiency and low inverter usage [62,72]. Moreover, its weight and volume are greater for the same power rating as compared to PM motors. These drawbacks of induction motor have been acting as speed bump in the race track. These

Table 9
Cost and weight domination of motor parts [30].

Electric motor parts	Cost (%)	Weight (%)
Motor core/lamination	45	55
Copper	10	15
Magnets	20	5
Housing and cover	20	25

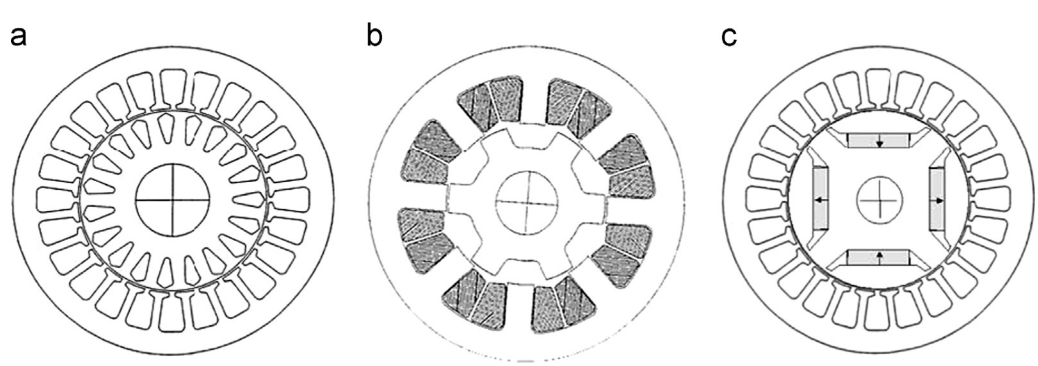

Fig. 10. Cross section view of (a) induction motor; (b) PM motor and (c) SR motor [62].

limitations have been taken into account by the researchers. Efforts are being made to resolve these issues either at design level or by proposing new control schemes and/or converter topologies.

3.2.3. Permanent magnet motor

Among all the available commutatorless motors, only permanent magnet brushless motors have the capability to compete against the induction motors in vehicle propulsion system [62]. In recent times, PM motors are widely accepted by the leading vehicle manufacturers for designing the existing and upcoming EPS. Generally PM motors are classified based on supply voltage and current as brushless DC and brushless AC. To maximize the torque density while keeping torque pulsation low, it is preferred to operate a PM machine in BLDC mode for trapezoidal back emf waveform and in BLAC mode for sinusoidal back EMF waveform [74]. PM motor possesses some inherent advantages: PMs excite the field which offers high power density as well as reduced weight and volume of the motor for given power rating; due to reduced rotor losses it offers highly efficient operation; compact packaging provides higher degree of reliability and maintenance free operation; effective dissipation of heat into atmosphere enables efficient cooling [60–65]. Despite their numerous advantages, PM motors have some limitations such as short constant power region due to limited field weakening capability. In addition control and management of back emf at high speed increases size and ratings of PECs and fault tolerant capability is an issue [63,74]. The extended speed range up to 3–4 times the base speed as well as enhanced efficiency of PM motors can be achieved by applying suitable control algorithms of power converters above the base speed [73]. Important design considerations for PM motors associated with fixed excitation for EPS include torque density, flux weakening capability, over load capability, stator iron losses, rotor eddy current losses and demagnetization withstanding capability.

The basic configurations of PM motors are classified based on the location of PMs. In conventional PM motors, PMs are mounted either on rotor surface or buried within the rotor. Surface mounted PM motors (SPM) are a widely used design and use less magnets whereas interior PM motors (IPM) use more magnets and offer higher air gap flux density with higher degree of ruggedness [76]. Therefore the interior PM motors are exceedingly being preferred for extended speed range, constant power operation over surface PM motors. In conventional PM motors, a compromise has to be made between low speed torque capability and high speed power capability. In order to overcome this problem the concept of hybrid PM motor and field excitation technique has been adopted [62,63]. Conceptually hybrid PM motor is either a combination of PM motor and reluctance motor or inclusion of additional field winding which limits air gap field. Thus the hybrid PM motors enhance the overall operational efficiency and offer wide speed, constant power operation with more complex structures. Availability, cost and supply issues with rare-earth PMs may affect their wide applications in EPS.

3.2.4. Switched reluctance motor

SR motor is gaining more and more attention for EPS in vehicular application. A SR motor offers tremendous potential for vehicular application especially for HEVs and FCVs [77,78]. The remarkable features of SR motors are: rotor without magnet and windings offers simple and robust construction which is desirable for very high speed as well as high temperature operation, excellent torque–speed characteristics, fault tolerant capability, constant power region can be extended up to 3–7 times, smooth and hazard free operation [60–65,77]. Limitations of SR motors include high acoustic noise, vibrations, high torque ripple, complex control mechanism and requirement of special converter topology. Although the cost of SR motors is relatively high, their mass production is expected to render them as cost effective as induction motors. All the advantages are prominent for vehicular application whereas the disadvantages are needed to be taken care properly to have feasible SR motor based EPS.

Comparison of different motors based on desirable characteristic for EPS is shown in Table 10. The suitability of particular motor at particular characteristic is rated in the scale of 1–5. Point 5 indicates the best suitability whereas point 1 shows the poor response. This comparison is indicative and measured in relative based on the existing literature; however it may vary with several factors like the design consideration of motors type, placement of motor (In wheel or out of wheel), material used for magnet, core and laminations, relevant power electronics converter and their

Table 10
Comparative analysis of different Electric Motors used in EPS [63].

Characteristic	Motors with commutator	Motors without commutator		
		Induction motor	PM motor	SR motor
Controllability	5	5	4	3
Size and weight	3	4	4.5	4
Robustness	3.5	5	4	4.5
Reliability	3	5	4	4.5
Power density	3	4	5	3.5
Efficiency	3	4	5	4.5
Speed range	2.5	4	5	5
Life time	3.5	5	4	4.5
Torque density	3	3.5	5	4
Technical maturity	5	4.5	4	3.5
Cost	3.5	5	3	4
Over load capability	3	4	4.5	4
Torque ripple/noise	3.5	4.5	4	3
Manufacturability	3	5	3	4
Potential for improvement	2.5	3	4.5	5

Table 11
Electric motor used in different electrified vehicles [62,63].

Make	Model	Market release	Electric motor	Power (kW)
Tesla	Model s	2012	IM	215
	Roadster	2008	IM	215
Hyundai	Blueon	2012	PM	61
Honda	Fit EV	2012	IM	49
	EV Plus	1997	DC	100
Toyota	Reva 4	2012	IM	50
	Prius	2004	PM	30
Honda	Fit EV	2012	PM	100
	Civic	2013	PM	17
Ford	Focus Electric	2011	IM	107
	Transit Connect	2010	IM	
	Think City	2008	IM	34
	Ranger EV	1999	IM	67
	ECOstar	1992	IM	56
Renault	Fluence ZOE	2011	SM	70
Tata Indica	Vista EV	2011	PM	55
Fiat	Peogeot ION	2011	PM	35
	Panda	2009	IM	15
REVA	NXR	2011	IM	13
Nissan	Leaf	2010	PM	80
	Altra	1997	PM	62
Mitsubishi	Miev	2009	PM	47
GM	EV1	1999	IM	102
Chevrolet	Volt	2011	PM	111
	Silverado	2010	IM	301
Mahindra Reva	Reva e2o	2012	IM	20
Holden	Ecommodore	2007	SR	55
Lucas	Chloride	–	SR	–

control algorithms etc. The main purpose of Table 10 is to bring out the most suitable motor technology for vehicular application. Electric motors being used by various commercialized model of electric and hybrid electric vehicles are given in Table 11.

3.3. Power electronic converters

Power electronics is an enabling technology for efficient electric power processing which plays crucial role in shifting the paradigm from conventional ICE vehicles to electrified vehicles [80]. The demand of electrical power in vehicular application is growing rapidly as the mechanical components are being replaced by the electrical and electronic components. It is expected that the power demand in electrified vehicle could reach 2–3 times of the current demand [81]. In order to accomplish the growing power demands of EPS in desired manner, integration of power electronic components with electrical and mechanical loads of vehicle becomes crucial. The integration of PEC not only improves the overall performance and fuel economy but also reduces the emission as well as the weight and size of the vehicle [80–83].

For sustainable EVT, there is a need of highly reliable, flexible and fault tolerant electrical power processing system on the board to deliver high quality of power based on vehicle demands. At present, this responsibility have been taken care by the available PEC that includes dc/dc converters, rectifiers (dc/ac), inverters (ac/dc) and battery charger composed of ac/dc and/or dc/dc converters. Individually or combination of these converters can be taken to serve the purpose; however, operation of each PEC is entirely different from the other. Conceptually PECs perform some of the critical tasks like ON/OFF switching of various loads; power conditioning and voltage/current modulation to create compatibility among the energy source system (ESS), traction motors and auxiliary loads. PECs not only serve the purpose of converting electrical power from one form to another (dc/dc, dc/ac and ac/dc,) but also help to step up or step down the system voltage level.

In the last decade, significant advancement in converter topologies dealing with battery charger, voltage source inverter for motor drives and dc/dc conversion has been achieved. Regardless of this topological advancement, still conventional PEC topologies are being used in modern electrified vehicles. Therefore, PECs for EVT can be categorized as shown in Fig. 11. The classification of the PECs is done based on their basic operation rather than topological advancement.

In EPS, there are two popular configurations to interface the ESS with inverter-motor drive as shown in Fig. 12: (a) a high voltage ESS is directly connected to inverter-motor drive;

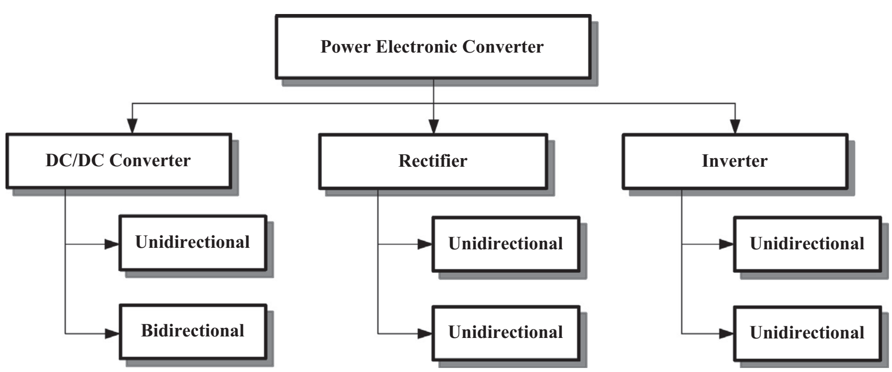

Fig. 11. Classification of power electronic converters.

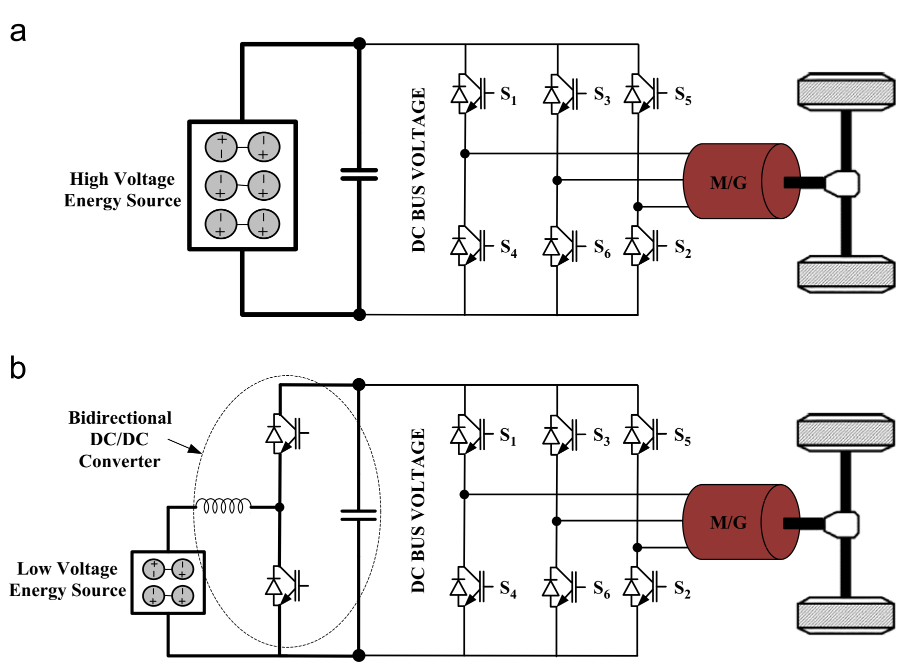

Fig. 12. Configuration of electric propulsion system: (a) interfacing of high voltage energy source; (b) interfacing of low voltage energy source with bidirectional dc/dc converter [82].

(b) a dc/dc converter is placed between low voltage ESS and inverter-motor drive [82]. In the first configuration, battery voltage level should match with inverter-motor drive's voltage level. This imposes certain constraints over the design and optimization of battery, inverter and motor. In the second configuration, addition of dc/dc converter increases overall component count but offers several advantages over first configuration. It boosts voltage level of ESS to match the rated voltage of inverter-motor drive. It provides bidirectional power flow between ESS and motor drive which assists rapid acceleration and recovers energy to charge the battery during deceleration and regenerative braking. It not only offers significant reduction in weight, size and cost of the ESS but also give the space for inverter control and motor design [82]. The efficiency analysis of both the configuration is presented in [85]. The role of bidirectional dc/dc converter is very significant especially in terms of better utilization of energy sources, power management, dynamic performance, flexibility, system optimization and reduction of weight and cost [84,89].

In HESs which is essential for vehicular application, a dc/dc converter is the key constituent which provides compatible interfacing and integration of energy sources. Apart from output voltage regulation, a well designed dc/dc converter can also control the power flow amongst different energy sources to load. Therefore, selection and design considerations of dc/dc converters are important factors in interfacing of energy sources. The detailed classification of dc/dc converter topologies for vehicular application is given in [82,89]. In addition, multiport dc/dc converter and multiple input interleaved converters are also employed for better energy diversification of the on board ESSS [90]. Therefore, the basic configuration shown in Fig. 12 can be further modified in the light of selection of dc/dc converter topology and ESS configuration.

In the advanced architecture of vehicle's electrical power system, it is expected to have a single dc voltage bus with the provision of different voltage level distribution and intelligent power and load management. The modern Architecture of electric power system for vehicular application is shown in Fig. 13. In this

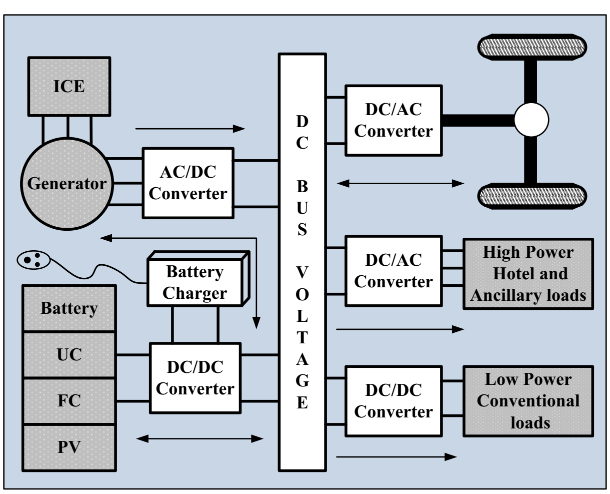

Fig. 13. Role of PEC in modern architecture of electrical power system for EPS.

architecture, different energy sources and vehicle loads having distinct *V-I* characteristics and dynamic response are interfaced with common dc bus through PECs. Since PECs are controlling, managing and optimizing the power flow among energy sources and vehicle loads, therefore it is considered as the heart of EPS whereas EPS is the heart of EVT.

The basic PECs contributing weight and volume of EPS are inverter, on-board charger, and bidirectional dc/dc converter. The main attention is being focused on bidirectional dc/dc converter for power flow optimization [88]. Apart from dc/dc converter, innovative efforts are also directed towards inverters which drive the traction motors and supply the auxiliary loads of electrified vehicle in desired manner. The selection of the inverter is based on the topology, power rating, type of motors and the packaging methods [80]. For PHEV, charging station demands appropriate battery charger composed of ac/dc and dc/dc converter. This configuration has two power stages. The first stage shapes the grid current for a unity power factor operation. The second stage regulates the battery charging current [92]. By using a converter with single-stage, advantages like simplicity in structure, higher efficiency, lesser number of components, and lower cost can be achieved as compared to a converter with two stages; however, battery current waveform remains unregulated [93]. The design of battery charger for PHEVs is based on battery capacity, electric circuitry, impact on utility grid, operator's safety, voltage level of vehicles etc [84]. The detailed analysis, classification and comparison of different battery chargers are presented in [92]. On the basis of published literature in the field, it can be observed that more emphasis has been given on improvement of particular converter type and its topology individually. Therefore, it is expected that significant reduction in component count, overall weight and cost can be achieved by innovative development of integrated dc/dc converter along with inverter and battery charger as the sole system as proposed in [93,94].

In EPS, power semiconductor devices like insulated gate bipolar transistors (IGBTs) and freewheeling diodes are key components, playing a critical role in all power electronic converters. Power semiconductor devices and their operating characteristic for PECs are summarized in Table 12 Power devices dominate in determination of performance, cost, efficiency and reliable operation of PECs. The emerging electrified vehicle market presents a tremendous business opportunity for the power device manufacturer; however certain technical hurdles to improve performance, operating temperature, reliability, packaging, and reducing manufacturing cost of the power semiconductor products need to be overcome [95].The application of wide band gap (WBG) and silicon carbide (SiC) devices in PECs leads to high-temperature capability, high-power density, high efficiency and reduces cooling system requirement. The suitable integration and packaging reduce component count, heat loss and improve heat transfer [29].

In addition to power electronic devices and controllers, there are several other components like capacitors, inductors, bus bar(s), heat sinks etc. which have significant influence in PEC design as shown in Table 13. The packaging techniques should ensure proper coordination and reliable operation of all these PEC components at extreme vibrations and high temperatures [29]. Available PECs are

Table 12
Power semiconductor devices for electric vehicular system [95].

Component	Semiconductor devices	Voltage rating (V)	Current rating (A)	Power rating (kW)	Switching frequency (kHz)
Inverter/rectifier for EPS	IGBTs/diodes	600–1200	100–600	20–100	5–30
DC/DC converter for EPS	IGBTs/diodes	600–1200	100–600	20–100	5–30
Inverter/rectifier for auxiliary loads	IGBTs/MOS-FET/diodes	600–900	15–60	2–4	5–50
DC/DC converter for low power loads	MOSFET/diodes	400–600	10–40	1–2	50–200

bulky and difficult to package for vehicular application, therefore, proper integration and packaging of power electronic components as sole system is one of the toughest and challenging tasks at present. In order to overcome hurdles and to meet the EV/HEV/PHEV/FCV electrical power requirement, the current research and development is focused on some technical challenges, such as development of new PEC (inverter, DC–DC converter, rectifier) topology that reduces the part counts, size and cost of the converters, reduction of passive element like capacitor and inductors that increases reliability, reduction of EMI and current ripples [30]. Suitable integration and packaging of these components will give the compactness in design which will lead significant reduction in overall weight and cost of PECs. Therefore, to meet future requirement for sustainable development of electrified vehicle new innovations and substantial modifications in power electronic converters are necessary from component level to system. The current trends and future status of electric motors, power electronic converter and EPS based on essential characteristics of vehicle application are summarized in Table 14.

3.4. Electronic controllers

The electronic control units are designed to provide supervisory control of electric vehicular system. It is a combination of dedicated system control software and electronic circuitry which includes interfacing hardware, sensing circuitry, driver and isolator circuitry and communication buses. Basically ECU is the integration of sophisticated electronic circuitry, dedicated digital controllers like microprocessors, microcontrollers, digital signal processors (DSP) and/or field programming gate array (FPGA); and modeling and simulation tools with auto code generation systems like MATLAB/Simulink, ADVISOR, PSAT, PSIM, SABER, SIMPLORER, VTB; along with embedded software [97–100].

ECU provides the flexible multi-input/output channels for communication among various components of the vehicular system. The controller synchronizes or coordinates with the components of EPS such as ESSS, PEC, electric motors along with ICE, transmission system, pilot commands and operating modes of the vehicle [101]. The ECU controls and maps the status of electric motor, ICE and vehicle behavior based on a selection of system inputs. Standard pilot commands, such as braking and acceleration are supplied as system input to the ECU from appropriate sensors and CAN buses. Based on system input and CAN bus information, certain mapping of different system components are performed to monitor their current status to select the vehicles mode of operation [100]. The entire information is processed in digital controllers through programming, which performs the required calculation and converted into desired power and/or torque and/or speed commands for each wheel individually or simultaneously [97]. The output of ECU which is driving signals for various components of the vehicle is communicated through CAN transmitter over different sections of vehicles. The ECU is not only able to implement a variety of advanced vehicle control and dynamics algorithms but it also monitors overall vehicle behaviors and observes the performance. The ECU is placed near to motor drives and engine, therefore it should be designed such that it can bear temperature ranging from 80–1400 °C and extreme vibrations which are major challenge. A self explanatory architecture of the ECU is shown in Fig. 14.

Table 13
Cost and weight contributions of PEC components [30].

Power converters components	Cost (%)	Weight (%)
Power switch/heat sink	33	33
Capacitor/inductor	20	22
Bus bars/connectors	13	15
Sensors	7	5
Housing and others	27	25

4. Power management and control algorithm

In EVT, the control and management of power flow from multiple energy sources to power electronic converters and from converters to different vehicle loads, is a major challenge. The technological advancement transforms the early ON/OFF control system to modern adaptive predictive control era that improves the overall performance of control system [102,103]. Dedicated efforts are being given for the development of appropriate control and energy management strategy which is very essential, specifically in HEV operation.

A control strategy is defined as an algorithm, which is a set of instructions or laws regulating the overall operation and power flow of the vehicular system. The algorithm can be considered as a black box that performs desired calculation on the basis of given information. Input information mainly contains measured data of vehicles operating condition such as acceleration, braking, torque demand, traffic information and driving profile. The outputs of the algorithms are decisions that command driver circuits to turn ON or OFF the vehicle's components or to modify their operating region towards optimization [102]. A properly developed control algorithm and management strategy should satisfy certain objectives such as vehicle power demand, monitoring of battery's state of charge, fuel economy, reduced emission, efficiency optimization and smooth coordination between electrical and mechanical components. Therefore it becomes prime concern to adopt systematic process for power flow control and optimization, while designing the controllers and control algorithms.

Controllers are mainly classified into two groups based on their mathematical modeling strategy; (1) rule based systems and (2) optimization based systems [101–107]. The detailed classification of both the controllers is given in Fig. 15. Basically, rule based controllers are designed to obtain maximum fuel economy, efficiency and reduced emission for predefined driving profiles. Rule based controllers are tuned based on sets of rules or criteria written on the basis of vehicle information. In this controller state diagram and flow charts are commonly used for performance

Table 14
Present and future status of EM, PEC and EPS [29].

Characteristic	Electric motor				Power electronic converter				Electric propulsion system			
	2010	2013	2015	2020	2010	2013	2015	2020	2010	2013	2015	2020
Power density (kW/L)	3.7	4.8	5	5.7	8.7	10.2	12	13.4	1.06	1.15	1.2	1.4
Specific power (kW/kg)	1.2	1.3	1.3	1.6	10.8	11.5	12	14.1	2.6	3.1	3.5	4.0
Efficiency (%)	90	91	92	93	91	92	94	97	90	91	93	95
Cost ($/kW)	11.1	9.5	7	4.7	7.9	6.5	5	3.3	19	16	12	8

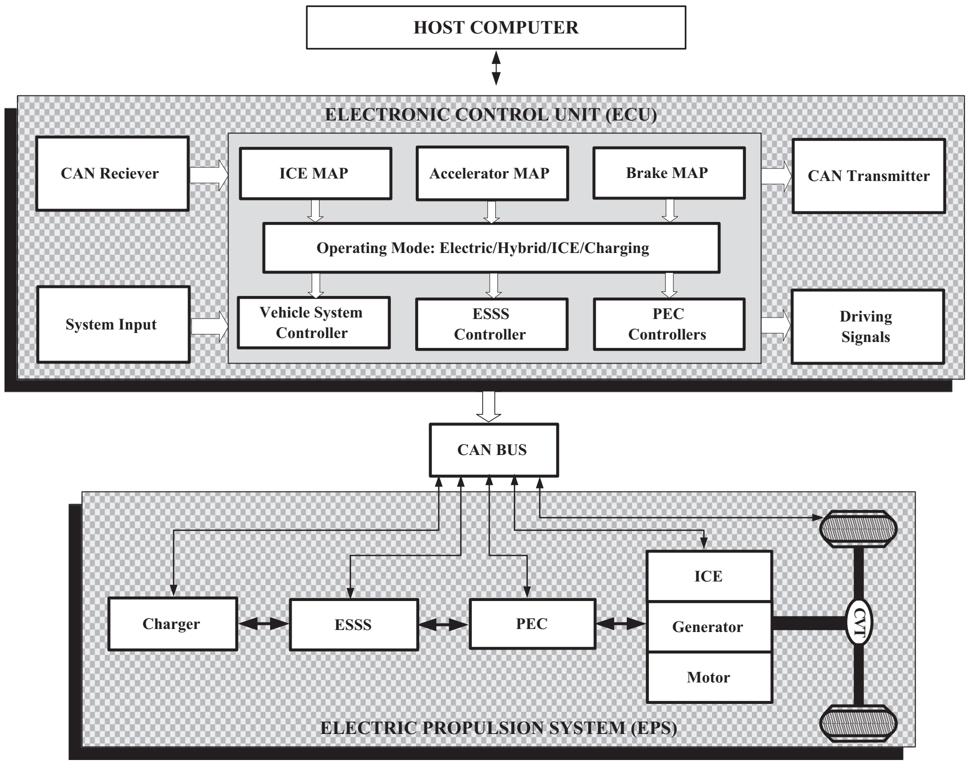

Fig. 14. Architecture of electronic controller for EV/HEV/PHEV/FCV.
Source: www.proteanelectric.com /Date: 09/03/2013.

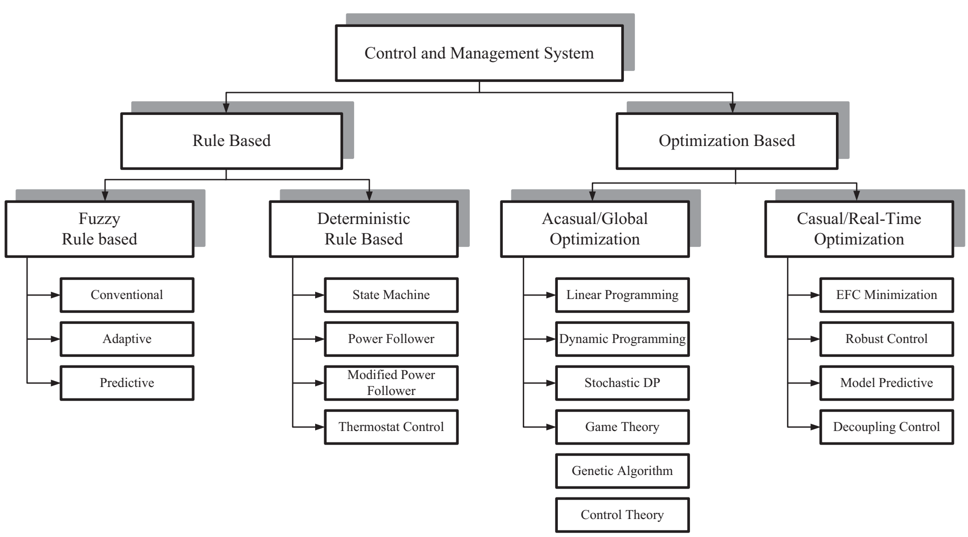

Fig. 15. Classification of control algorithms and power management techniques for EVT [104].

optimization of each component individually rather than cumulative. On the other hand optimization based controllers are designed to develop optimal control strategy for propulsion system by reducing the cost function. The cost function is derived based on the past and future information of driving profile, component parameters and expected performance of the vehicles. This controller is tuned for overall vehicular system optimization rather than component level [105]. Both the controllers have their own pros and cons which are summarized in Table 15, and need to

Table 15
Comparison between rule based and optimization based controllers.

	Rule based	Optimization based
Implementation	Simple	Complex
Speed	Fast	Slow
Sensitivity	Low	High
Optimality	Approximate	Exact
Information needed	Less	More

be addressed properly before implementing the algorithms. The global control strategy with real time optimization has been the best proposed solution for HEV/PHEV so far [103].

5. Conclusion

In this paper, topological configuration of different vehicles has been reviewed with emphasis on electric propulsion system and its components. Contemporary and futuristic global scenario of environmental, political, economical and technological factors has accelerated the interest towards partial and/or complete electrification of vehicular technology. A comparative analysis of EVT shows that the different electrified vehicles are at different stages of evolution and commercialization. EVs/HEVs are gradually commercializing and capturing a significant market space. PHEV's are ready to be commercialized. Suitable energy policy and infrastructures for charging station will accelerate the commercialization of plug in HEVs very soon in near future and it will sustain for a long time. FCV's are under development and are yet to be commercialized. Fuel cell vehicle can be seen as the future of transportation system with suitable technological advancement. Despite these developments, the members of EVT face different technical and nontechnical challenges and require certain targeted strategies and planning for their commercialization.

The sustainable development of EVT heavily depends on electric propulsion system and its components. The comprehensive review of EPS indicates that the recent modification in EPS due to technological advancement of its members like ESS, power electronic converter, electric motor and electronic controllers, makes EVT capable to compete against conventional ICE based vehicular technology. For successive advancement of EPS, technical breakthroughs are necessary from device level to system level, so that improved performance, higher efficiency and reliability can be achieved. The suitable integration and packaging of these components is a challenging task that needs to be addressed properly so that significant reduction in weight, volume and cost can be expected with better cooling system and reliable operation. The successful penetration of EVT will mainly depend on the substantial technological advancement of EPS and its components that in turn decide dynamic performance, fuel economy, durability and cost of the vehicle.

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